Harnessing fusion power: how does CT research contribute to this discussion?

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Abstract. Although many issues seem universal, several distinct issues in harnessing fusion power could be helped by using a CT core. By omitting the OH and TF coils, the system becomes simpler, more compact and hence easier to maintain and repair, which should allow for higher availability. Fewer complicated components perhaps means that the system will be more reliable. A simply-connected system could lend itself to the exploration of liquid first walls. The starting point for the discussion is the Greenwald report and subject areas are organized according to the categories defined there, then a summary of the ReNeW Theme IV workshop, and ideas presented there.

I. Introduction: closing the gaps.

Starting point for the discussion is the Greenwald report [1]. In it, there are several research gaps pertaining the harnessing fusion power that are discussed:

> *G-10. Understanding of the use of low activation solid and liquid materials, joining technologies and cooling strategies sufficient to design robust first-wall and divertor components in a high heat flux, steady-state nuclear environment.*
>
> *G-11. Understanding the elements of the complete fuel cycle particularly tritium breeding and retention in vessel components.*
>
> *G-12. An engineering science base for the effective removal of heat at high temperatures from first wall and breeding components in the fusion environment.*
>
> *G-13. Understanding of the evolving properties of low activation materials in the fusion environment necessary for structural and first wall components.*
>
> *G-14. The knowledge base for fusion systems sufficient to guarantee safety over the plant life cycle - including licensing and commissioning, normal operation, off-normal events and decommissioning/disposal.*
>
> *G-15. The knowledge base for efficient maintainability of in-vessel components to guarantee the availability goals of Demo are achievable.*

In response to these gaps, the ReNeW Theme IV ‘Harnessing Fusion Power’ organized into five thrusts: 1. Fuel Cycle; 2. Power Extraction; 3. Materials; 4. Safety; and, 5. Reliability, Availability, Maintainability and Integratability (RAMI). White papers are online at the Theme IV website [2]. The current thought is that DEMO will be a DT burning, large aspect-ratio tokamak with some critical issues that do not yet have a solution – for example, one of the most pressing concerns is the availability of a tokamak reactor if there is a failure in the TF coil – large systems may need to be switched off for some time. DEMO aims for 50% power availability, although to do so means that there has to be an even more radical design to ensure that this is possible. Here we discuss each of the thrusts and their critical issues and ways in which CT research could impact the thinking. It should be emphasized that while the core can be compact, the core is only one component of the system for harnessing fusion power. By inclusion of all of the other systems (in particular: heat extraction, tritium handling, and remote handling), the effect on total capital cost of the *plant* by use of a different magnetic configuration (with similar confinement) becomes small. However, the CT community has some opportunities (and arguably a necessity) to think around current problems facing DT-burning tokamak DEMO designs: opportunities exist for contributing to all of the thrusts.

This paper is structured as follows. Section II contains an outline of what might happen if the OH and TF coils are omitted. Section III summarizes each of the thrust areas and discusses opportunities for CT research. Section IV is a summary.

II. CT geometry: omission of TF and OH coils.

There are some intrinsic geometrical effects that would be important if the physics of the concept proves favorable (i.e. similar confinement properties to tokamaks in steady-state): CTs do not have toroidal field coils nor central column and central blanket, and so the confinement volume is simply-connected. Fewer components, and non-interlocking coils means that disassembly and maintenance would be possible on more favorable time-scales.

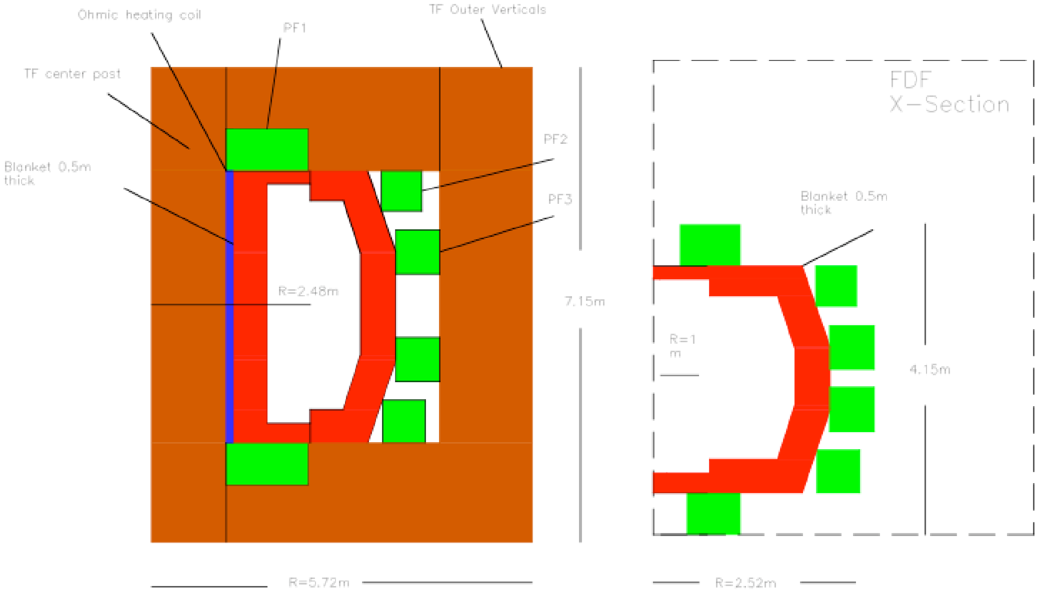

Figure 1. Sketches of Tokamak and CT cores for similar plasma volumes. Left: Fusion Development Facility (FDF) [3]. Right: similar system without the TF + OH coils, and central blanket.

III. Summary of thrusts and suggestions of how CTs could impact them

III.1 Fusion fuel cycle

This thrust examines how the fuel is put into the system, how it is bred, and how it is extracted from the breeding process and recovered from the surfaces of the vessel, how it is monitored and accounted. The critical issues here are that Tritium is quite difficult to manufacture – large scale production facilities are needed to actually make enough of it for a DEMO, and these don't exist: TSTA generates 6l/minute of Tritium, where 120l/minute will be needed for ITER and DEMO. Next, the tritium that is produced is difficult to extract both from the blanket and from the first wall. There are no known ways to fully extract Tritium from a system once it is in there, and control of the breeding needs to be very carefully done. By use of a difference fuel cycle, it is possible to avoid many issues posed by the D-T cycle [4]. CT plasmas have not disrupted nor have they produced ELMs.

III.2 Power extraction

This thrust examines how the heat is extracted from the plasma by use of blankets and divertors, but also entails other subsystems, such as baffles, 1st wall shield, coolant loops, heat exchangers and power conversion components. Main issues are to not only to understand thermal fluid dynamics and generation of tritium, but also to understand how the system integrates into the fusion core. Understanding thermal gradients in the coolant flow, means for controlling coolant chemistry and effects of fusion environment with strong magnetic field remain to be resolved. By simplifying the geometry, particularly by omission of the central blanket, a CT blanket may be easier to fabricate, though most issues will remain.

III.3 Materials

This thrust examines which materials can be used in a system with high heat and neutron fluxes to surfaces. The fusion environment does not remain still on any scale-length, and so thermal and mechanical stresses have to be considered on all scale lengths. Largely, the call is to extend the database of materials from samples to components. A testing facility would be needed to do the large-scale materials testing. Currently, the tokamak / ST CTF are thought to be the only possible candidates for volumetric sources, although a mirror-CTF based on the GDT is discussed [5]. Spallation sources are also proposed. One possible advantage of a simply connected volume and simple flow pattern might be that liquid first walls can be used to protect other surfaces (see e.g. Majeski's white paper [6]).

III.4 Safety

This thrust examines how one maintains an inherently safe device. The Greenwald report summarized these as (1) ability to not require an evacuation plan; (2) generate only low-level waste; (3) ability to not disturb the public's day-to-day activities; (4) ability to not expose workers to a higher risk than other power plants; and (5) demonstrate a closed tritium fuel cycle. With a simpler system it is possible that the safety issues are reduced also.

III.5 Reliability Availability Maintainability Integrateability

Ultimately, the power core will be installed as a power producing plant, generating electricity in an economic manner. This theme examines how the core and subsystem design impacts the CoE, and poses categories for assessing economy.

III.5.1 Reliability

How to make a system as reliable as possible? Comparisons are made between the DEMO and a fission power station of similar output power – the fusion system entails many more components and subsystems. The subsystems are also increasingly high tech, not low, and so the issue of reliability of a highly complex system is questionable. CTs offer relatively simple systems, particularly if heating and current drive systems are combined into a single unit.

III.5.2 Availability

In the event of a failure, how will the system be repaired expediently? The cost of electricity scales inversely with availability, so down-time has to be minimized. The ability, in the event of a failure to replace major subsystems quickly could be critical – for example, a failure in the TF leg in the tokamak does not currently have a fix shorter than 2 years, DEMO will need to do the replacement in days. To be taken seriously by the utilities there has to be a minimum of 50% plant availability, that pushes the fusion core to need at least 80% availability. The GA FDF facility proposes to address this issue by making the system highly modular (mountable annular sections, not wedges, demountable toroidal coils). Because the CT has fewer major components, the likelihood of long down-time is reduced, and so CT plants could have higher availability.

III.5.3 Maintainability

Are modular systems needed? The view of a reactor being constructed as a 'ship in a bottle' no longer is valid as highly modular systems are being designed – with either wedge or annular sections. Simply connected systems will have advantages here, particularly if the coils are not interlocking, which would allow for easy annular construction.

III.5.4 Integrateability

How are complicated modular systems integrated into a coherent whole? Reducing the system complexity serves easier integration.

IV. Summary

Although many of the issues remain common, by omitting the OH and TF coils, the system becomes simpler, more compact and hence easier to maintain and repair, which should allow for higher availability. Fewer complicated components perhaps means that the system will be more reliable. A simply-connected system could lend itself to the exploration of liquid first walls. However, despite possible implications for reactor designs, the CT physics remains at the CE level of development, and so focus in the CT program must remain on proving the physics of confinement, stability and current drive.

[1] M. Greenwald, Chair. Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan For Magnetic Fusion Energy Report to the Fusion Energy Sciences Advisory Committee October 2007
[2] http://burningplasma.org/web/renew_whitepapers_theme4.html
[3] R. D. Stambaugh Fusion Development Facility (FDF) Mission and Overview APS, November, 2007 **http://web.gat.com/fdf/**
[4] J. Sheffield D-D Power Plants: the ultimate fusion goal, White paper submitted to ReNeW Theme IV
[5] A Materials Evaluation D-T Neutron Source Based on an Axisymmetric Gas Dynamic Trap Magnetic Mirror, by the Mirror Study Group, Chairman: T.C. Simonen, submitted to ReNeW workshop
[6] Dick Majeski, Jean Paul Allain, Hantao Ji, Neil Morley, Mark Nornberg, and David Ruzic Liquid Metal Plasma –Facing Components